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InP Concentrator Solar Cells for Space Applications

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ABSTRACT

The design, fabrication and characterization of high-performance, n^+/p InP shallow-homojunction (SHJ) concentrator solar cells is described. The InP device structures were grown by atmospheric-pressure metalorganic vapor phase epitaxy (APMOVPE). A preliminary assessment of the effects of grid collection distance and emitter sheet resistance on cell performance is presented. At concentration ratios of over 100, cells with AM0 efficiencies in excess of 21% at 25°C and 19% at 80°C are reported. These results indicate that high-efficiency InP concentrator cells can be fabricated using existing technologies. The performance of these cells as a function of temperature is discussed, and areas for future improvement are outlined.

INTRODUCTION

In the past several years, InP solar cell performance has begun to approach the high conversion efficiencies predicted by the early modeling efforts [ref.1]. With reported end-of-life/begining-of-life ratios (EOL/BOL) for efficiency of about 90%, the radiation resistance of InP is generally acknowledged to be superior to both GaAs and Si [ref. 2]. At this point, one of the major obstacles to a more widespread use of InP in space is the price of high-quality, single-crystal substrates. Various strategies have been suggested to limit the impact of this cost. These strategies include the development of multijunction cells to boost efficiency, heteroepitaxial growth techniques, which would eliminate the need for InP substrates, and concentrator cells, which would greatly reduce the impact of their cost. Overlapping efforts in all three of these approaches are currently being pursued at the Solar Energy Research Institute.

Recent work on space photovoltaic concentrator arrays indicate that attractive power densities and power-to-mass ratios are achievable with these systems [ref.3]. While excellent work is being done concerning the effects of the space environment on concentrator modules, the possibility that radiation effects may prove to be problematic for these systems cannot be overlooked. InP may prove to be a radiation-resistant alternative to GaAs. InP concentrator cells have the potential for high conversion efficiencies [ref. 2] and their high EOL/BOL could make space photovoltaic concentrator arrays competitive with more conventional flat-plate systems.

The work done on InP concentrator cells should yield information that will be directly applicable to the emerging heteroepitaxial cell technology. We have already seen dramatic improvements in the performance parameters of heteroepitaxial InP cells when measured under solar concentration.

Improving the performance of the SERI-designed $InP/Ga_{0.47}In_{0.53}As$ monolithic tandem cell requires advances in the design of the InP top cell [ref. 4]. The $Ga_{0.47}In_{0.53}As$ bottom cell is exhibiting near theoretical performance levels but the InP top cell is showing evidence of series resistance problems at concentration ratios above 40 suns. Minimization of these series resistance losses may allow the tandem efficiency to exceed 30% AM0, (At 28.8%, AM0, 40 suns, 25°C, this is already the most efficient monolithic photovoltaic device yet demonstrated).

In previous work [ref.5], we performed an empirical investigation of the InP SHJ solar cell designed to operate at one sun. Optimum design parameters were identified and devices were fabricated that yielded one-sun AMO efficiencies of 17.6% at 25° C. A thin (25 nm) emitter was found to be essential to minimize the roll off in the blue response attributable to the unpassivated InP surface. For concentrator cells, the benefits of this enhanced blue response must be weighed against the high sheet resistance associated with thin emitter designs. At one-sun current densities (~35 mA cm^{-2}) the negative effects of the high sheet resistance can be minimized by adjusting the grid finger spacing. However, our concentrator cells utilize Entech prismatic covers [ref.6] originally designed for GaAs concentrator cells operating at 100 suns. This aspect of our concentrator cell design results in the grid line spacing being fixed at 127 μm. Therefore, it is reasonable to expect that the optimum concentrator cell structure may differ from the optimum one-sun structure. In this paper we describe our initial efforts to fabricate high-performance InP concentrator cells designed to operate under 100 AM0 suns.

DEVICE DESIGN

A schematic diagram of the InP concentrator solar cell structure is given in figure 1. The devices are grown by APMOVPE on Zn-doped, p^+ substrates oriented in the (100) direction. Growth is carried out in a vertical reactor vessel at a temperature of 620°C and in a purified hydrogen ambient. The primary reactants are trimethylindium and phosphine. The dopants consist of hydrogen sulfide and diethylzinc. A p^+- back-surface-field layer that is grown to a thickness of 0.38 μm, is followed by a p-base layer that is doped to ~ 10^{17} cm^{-3} and grown to a thickness of 3.8 μm. The thin n^+ emitter layer, that is doped to 3.7 x10^{18} cm^{-3} completes the growth.

After etching the back surface in a 1% by volume Br in MeOH solution for 5 minutes, an ohmic contact is formed by electroplating 0.1 μm of Au, 0.1 μm of Zn, and 3 μm of Au onto the back surface and then annealing it on a graphite strip heater at 375° C for 90 seconds. The grid pattern on the emitter surface is defined by standard photolithography and pure Au is electroplated to a thickness of 5 μm. Cell isolation is accomplished by an HCL etch after a photolithographic mesa definition. The devices are completed with the deposition of a ZnS/MgF_2 anti-reflection coating and application of prismatic covers. (See fig.1)

The Entech prismatic cover is an essential component of the cell design. With the resistivity of electroplated gold often in excess of five times the bulk value [ref. 7], metalization schemes designed to handle current densities of 3.6 A per cm^2 necessarily entail a high grid coverage (~20%). We have found that with a properly designed anti-reflection coating, the optical losses associated with the use of the prismatic cover are under 5%. The major limitation associated with the use of the cover for this device is that the grid line spacing is fixed.

EXPERIMENTAL

Our primary objective in this work was to demonstrate the potential of InP concentrator cells. However, development of the single-junction InP concentrator cells is important as a basis of comparison with the heteroepitaxial cells and the $InP/Ga_{0.47}In_{0.53}As$ tandem. As a starting point in our attempt to optimize the InP SHJ cell structure for operation under concentration, we decided to examine the effects of grid finger spacing and emitter layer sheet resistance on cell performance.

The three-terminal design of the monolithic $InP/Ga_{0.47}In_{0.53}As$ tandem cell uses a prismatic cover slip with a fixed center-to-center grid line spacing of 127 μm. In the three terminal configuration, every other grid line must be used for the middle contact. Both the top contact fingers and the middle contact moats are 25 μm wide, resulting in a grid finger collection distance (S/2) of 102 μm. Hall and electron probe measurements on our n^+-InP layers provide values of 1200 $cm^2 V^{-1} s^{-1}$ for the electron mobility and 3.7 x 10^{18} cm^{-3} for the free electron density. This results in a resistivity value of 1.4 x 10^{-3} ohms-cm. Using the emitter thickness of 24 nm, the computed power loss at 100 suns due to lateral current spreading in the emitter is about 8%. This is an unacceptably high level for this component of the series resistance. When measured under solar concentration, the top cell of the tandem exhibits evidence of becoming series resistance limited beyond a concentration ratio of 40 suns. From the power loss calculation, we conclude that the drop in efficiency for the top cell of the tandem at concentration ratios above 40 is caused primarily by a non-optimum grid line spacing.

As a test of this hypothesis, we fabricated single-junction InP concentrator cells that use a grid line spacing of 127 μm. The effective collection distance in this case is one-half of the tandem's collection distance, or

51 μm. Due to the S^2 dependence of the power losses in the emitter, this gives a reduction by a factor of four from 8% to 2%, which is a more reasonable level for this loss mechanism. We also fabricated cells with emitter thicknesses of 33 and 240 nm in order to test whether a lower emitter sheet resistance would result in a further power loss reduction under concentration. The computed lateral sheet resistance power losses associated with these designs are 1.6% and 0.02%, respectively.

The performance of these cells was characterized by absolute external quantum efficiency (AEQE) measurements as well as illuminated current-voltage characteristics as a function of the concentration ratio. All measurements were made at both 25 and 80°C. All efficiencies reported here are referenced to the AM0 spectrum [ref.8]. The cell performance is discussed in the following section.

RESULTS AND DISCUSSION

When one compares the efficiency as a function of concentration for the single-junction cells with that of the top cell of the $InP/Ga_{0.47}In_{0.53}As$ tandem (fig. 2), it is apparent that the series resistance problem occuring between 40 and 100 suns is greatly reduced in the single-junction design. Furthermore, when the fill factor as a function of current density for the single-junction device with the 33 nm emitter is compared to that of the device with the 240 nm emitter (fig. 3), the similarity in behavior suggests that the resistance due to lateral current spreading in the emitter is not a major power loss mechanism for this concentrator grid design. The above mentioned power losses for this component of the series resistance are consistent with the observed performance of the cells. This implies that a grid pattern with a finger spacing compatible with available Entech prismatic cover material is adequate for the fabrication of high-performance InP SHJ concentrator cells operating at 100 suns.

The single-junction InP concentrator cell design utilizing a 33 nm-thick emitter has achieved high efficiency levels at concentration ratios of over 100 suns. Peak efficiency under the AM0 spectrum at 25°C was 21.4% at a concentration ratio of 106.5 suns. This represents a gain of 2.3 efficiency percentage points compared to the best reported one-sun result of 19.1% at 25°C [ref. 9]. The efficiency dropped to 19.1% at 80°C and 125 AM0 suns (fig. 4). This high-temperature result is particularly relevant to operation under concentration where 80°C is considered to be a realistic temperature for passive cooling at 100 suns.

Analysis of the AEQE data (not shown here), indicates that improvements in the performance of these cells will likely be achieved by fabricating devices with even thinner emitters, which will enhance the blue response and increase J_{sc}. Development of a passivating window layer should have a similar effect as well as providing a possible increase in V_{oc}.

SUMMARY

As part of an ongoing effort to make InP-based solar cells a realistic option for the space community, InP concentrator cells have been fabricated and characterized as a function of concentration ratio and temperature. AM0 conversion efficiencies of 21.4% at 25°C and 19.1% at 80°C have been achieved. The power loss due to lateral current spreading in the emitter layer was found to be within acceptable limits using a grid design that incorporates an available Entech prismatic cover. These results indicate that the necessary technologies presently exist for the fabrication of high-performance InP concentrator solar cells.

The InP concentrator cells described in this paper have attained a high level of performance utilizing well developed growth and processing techniques. Areas for further research include a more detailed look at the optimum emitter thickness for the present shallow-homojunction design. Higher efficiencies are expected for devices with slightly thinner emitters. We intend to apply low-resistance, highly adhesive metalization schemes currently being developed at SERI to these cells in the near future. Surface passivation is perhaps the best approach to further reducing the losses due to the sheet resistance of the emitter since thicker emitter layers could ultimately be employed. Experimental evidence suggests that at 80°C and at the current densities observed at 100 suns, these devices may become self-annealing. The power-to-mass ratios of certain space concentrator systems can be improved if radiation tolerance can be eliminated as a design constraint.

The InP concentrator cell comprises the top cell of the most efficient monolitic device yet demonstrated (the InP/$Ga_{0.47}In_{0.53}As$ tandem). This work has shown that minor design changes in the top cell of the tandem will result in an improved level of performance. When these designs are incorporated into the InP/$Ga_{0.47}In_{0.53}As$ tandem, AM0 conversion efficiencies in excess of 30% are anticipated.

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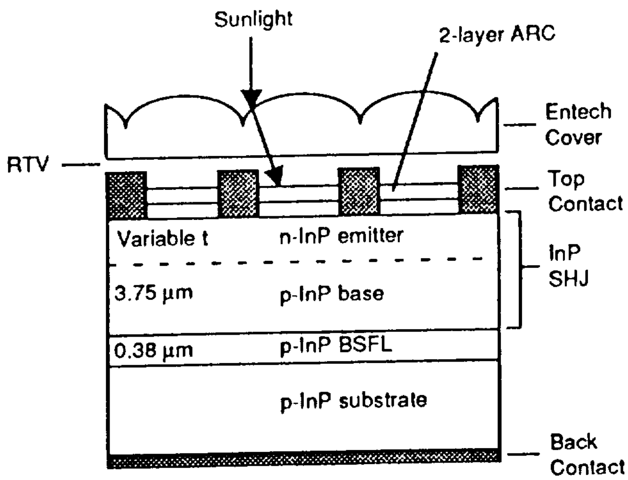

Figure 1. Cross-sectional schematic diagram of the InP shallow-homojunction concentrator solar cell structure.

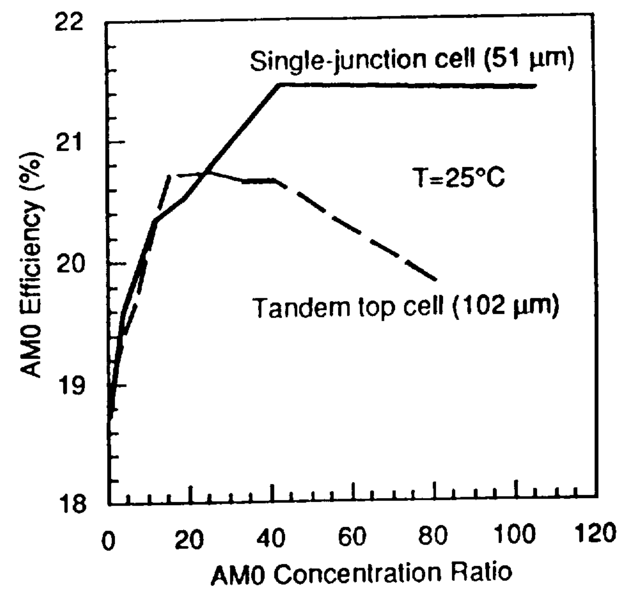

Figure 2. AM0 efficiency *versus* concentration ratio data for InP concentrator cells with similar structures, but different grid collection distances.

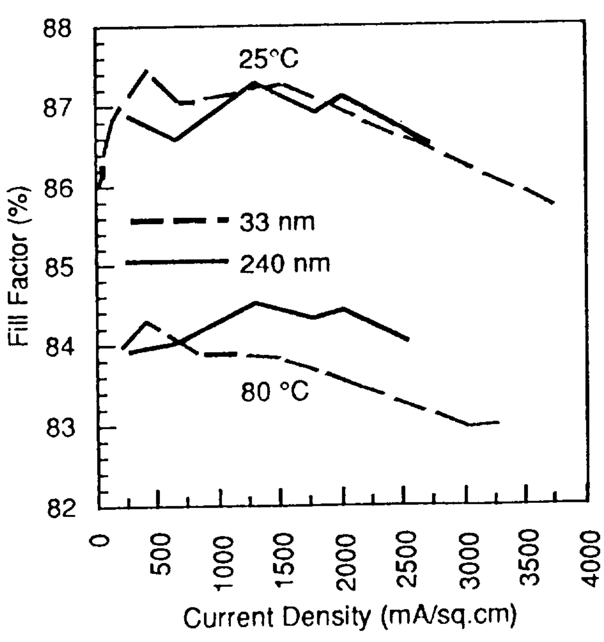

Figure 3. Fill factor *versus* current density data for InP concentrator cells with the same grid collection distance (51 μm), but different emitter thicknesses.

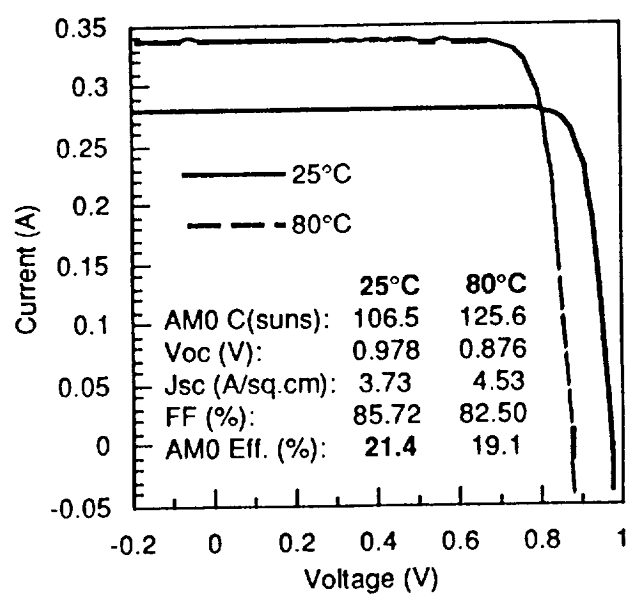

Figure 4. Current-voltage data for an InP shallow-homojunction cell at peak AM0 efficiency under concentration at 25°C and 80°C.